

Applicability of entropy, entransy and exergy analyses to the optimization of the Organic Rankine Cycle



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ABSTRACT

Based on the theories of entropy, entransy and exergy, the concepts of entropy generation rate, revised entropy generation number, exergy destruction rate, entransy loss rate, entransy dissipation rate and entransy efficiency are applied to the optimization of the Organic Rankine Cycle. Cycles operating on R123 and N-pentane have been compared in three common cases which are variable evaporation temperature, hot stream temperature and hot stream mass flow rate. The optimization goal is to produce maximum output power. Some numerical analyses and simulations are presented, and the results show that when both the hot and cold stream conditions are fixed, all the entropy principle, the exergy theory, the entransy loss rate and the entransy efficiency are applicable to the optimization of the ORC, while entransy dissipation is not. This conclusion is available no matter what kind of working fluid is used, nevertheless, the system performances and parameters may be much different. The results also indicate that when the hot stream condition (temperature or mass flow rate) varies, the entransy loss rate is the only parameter which always corresponds to the maximum power output.

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1. Introduction

Global energy demands escalating at a dramatic speed are contradict with global warming attributed to a large extent, to significant rise in the use of fossil fuels for electricity generation. However, it must be conceded that economic development and energy consumption are closely associated. Up to now over a half of the low or moderate temperature heat sources (~ 773.15 K), e.g. as solar energy, biomass energy, geothermal energy and waste heat are directly rejected to the environment. How to recovery these parts of low-grade heat attracts large attention for the purpose of energy conservation and thermal pollution reduction. Although heat recovery has huge potential and is around the corner, but the progresses of the technologies still require more research and development.

Recovery system based on the ORC (Organic Rankine Cycle) [1–38] with heat input and power output reversing low-grade heat into high-grade electricity with its simplicity and commonly available components has been widely discussed in recent decades. Analyses [33–38] of the ORC are mainly around the first and second law efficiency by thermodynamics. In this paper, we

distinctively consider the applications of some theories, such as entropy generation, exergy destruction concepts and entransy theory.

Entropy generation minimization is always related to the optimal output and minimized irreversibility since it stands for the ability loss of doing work. However, in recent years there are some different voices, the applicability of this theory is challenged. It was found not lead to the maximum system performance all the time unless the refrigeration capacity is prescribed [39,40].

The entransy theory [41–51] was proposed by Guo et al. [41] and developed for optimization design of thermal system and heat transfer. It is a quantity corresponds to the electrical potential energy in a capacitor, and now it is defined to describe the “potential energy of heat” in heat exchangers or heat-work conversion systems. It was also investigated to analyses of heat-work conversion processes by Cheng [42–46] as the “ability to release heat of the system”. The results show that the increase in output power is corresponding to the increasing entransy loss. Yang et al. [47] applied the entransy theory and finite-time thermodynamics theory to research a two-heat-reservoir heat engine model with heat leakage, finite heat capacity high-temperature source and infinite heat capacity low-temperature heat sink. Their results are classified into three different cases. Wang et al. [48] extended the entransy theory to the steam power cycle and proved that it can serve as an approach of optimization. Zhou et al. [49] analyzed

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Nomenclature

C	heat capacity flow rate, kW/K
c	specific heat capacity, kJ/(kg K)
$\dot{E}_d$	exergy destruction rate, kW
e	specific exergy, kJ/kg
G^*	entransy efficiency
$\dot{G}_{dis}$	entransy dissipation rate, kW K
$\dot{G}_f$	heat entransy flow rate, kW K
$\dot{G}_{loss}$	heat entransy loss rate, kW K
M	molar mass, g/mol
$\dot{m}$	mass flow rate, kg/s
N_{RS}	revised entropy generation number
h	specific enthalpy, kJ/kg
P	Pressure, kPa
$\dot{Q}$	heat exchange rate, kJ/s
$\dot{S}_f$	entropy flow rate, kW/K
$\dot{S}_g$	entropy generation rate, kW/K
ΔS	entropy change rate, kW/K
s	specific entropy, kJ/(kg K)
T	temperature, K
$\dot{W}$	power output, kW

Subscripts

0	environment
1–16	state points of the cycle
bp	boiling point
c	cold stream
$cond$	condensation
cr	critical
$evap$	evaporation
exp	expansion
fp	fusing point
H	high temperature side
h	hot stream
in	flow into the system
L	low temperature side
out	flow out of the system
pp	pinch point
$pump$	working fluid pump
r	working fluid
sub	subcooling
sup	superheating
$total$	the total system

and optimized Stirling cycle by taking the maximum output work as an objective, and discussed suitability of entransy loss, entransy dissipation, entropy generation, number of entropy generation, and improved number of entropy generation in optimization of system parameters, and the results showed that the consistency of entransy loss was better than others when it was applied to optimize the output power of Stirling cycle. However, the organic Rankine cycle is far different from the steam power cycle with working fluids, heat stream temperature range and circulation way. For steam Rankine cycle, the suitable working fluid is only water (wet fluid), thus not many conditions need to be considered. However, for ORC, dry fluids or adiabatic fluids are used to generate. Beyond that, ORC is an approach to recovery the waste heat from the exhaust gas from steam Rankine cycle, therefore the gas inlet temperature of ORC is always lower than that of steam Rankine cycle. Besides, steam Rankine cycle usually adopts steam turbine as power machine, however, ORC utilizes screw or scroll expander to replace the turbine. That means the efficiencies and efficiency correction factors of the power machines are different. Since there are many differences, whether the entransy theory can be applied to any fluid and temperature range of ORC is need to be verified. The applicability of the entransy theory to ORC still needs further discussions for lack of reports.

Mago et al. [8] applied exergy destruction to ORC operating on R113, the result demonstrates that for the ORC the evaporator is the component with the highest exergy loss contribution (77%) followed by the expander with 21.4%. Moreover, he summarized that the total system exergy loss decreases with the evaporator pressure increase in the analyzed case.

In this paper, R123 and N-pentane are chosen as working fluids and compared by different indicators. The concepts of entransy loss and dissipation are applied to the analyses of the ORC. The relationship of the concepts of entropy generation, entransy loss, entransy dissipation, exergy destruction and the output power for ORC are derived and demonstrated under both fixed and variable hot stream conditions. Different evaporation temperatures, hot stream inlet temperatures and mass flow rates are simulated so as to find the variation tendency of the concepts mentioned above. The article firstly analyzed the Organic Rankine Cycle and introduced the difference with steam Rankine cycle in Section 2.

And then it expressed the formulas and the derivation processes of the evaluation indicators in Section 3. After that, in Section 4, the global model including hot and cold stream conditions, brief assumptions, and working fluids properties is given. Finally, 3 typical cases have been taken into consideration to give a crosswise comparison in Section 5. Results prove that the entransy loss rate can be a method to optimize the output power of ORC in all the three cases, which gives us a train of thoughts that when designing the system operating condition, finding the maximum entransy loss rate is same to getting the maximum output power. However, other concepts which are widely used are not suitable for all three cases.

2. Analyses of Organic Rankine Cycle

Fig. 1 shows that the elementary configuration of ORC system contains an evaporator, an expander, a condenser, a working fluid pump and a cooling cycle. The evaporator and the condenser are both expressed as three-step models by Quoilin et al. [15] and Wei et al. [9]. The thermodynamic processes on the T - S diagram for the ideal ORC system corresponding to the numbers in Fig. 1 are illustrated in Fig. 2 where the tawny curve connecting points 4, 7, 8 and 3 is the saturation curve. The whole system is under equilibrium state and stable, without leakages, mechanical and heat losses. In the following, the quantities T_i , P_i , h_i , and s_i denote the temperature, the pressure, the specific enthalpy and the specific entropy at state point i and the quantities $\dot{W}_{i,j}$ and $\dot{Q}_{i,j}$ denote the specific work and heat in the process from state point i to state point j .

At state point 1, the working fluid with pressure P_1 , temperature $T_1 = T_{evap} + T_{sup}$ is superheated vapor, then it enters the expander where it undergoes an expansion till it arrives at point 2 with pressure P_2 , temperature T_2 , $s_1 = s_2$. During the expansion, work $\dot{W}_{1,2} = \dot{m}_r(h_1 - h_2)$ is delivered from the expander. At state point 2 the working fluid enters the condenser in which it returns isobarically to subcooled state point 5 by releasing the specific heat $\dot{Q}_{2,5}$ to the cold stream. At state point 5 whose temperature and pressure are the lowest ones in the ORC, the working fluid is subcooled liquid at $T_5 = T_{cond} - T_{sub}$ and the corresponding vapor

$$\dot{S}_g + \dot{S}_f = \Delta \dot{S} \quad (13)$$

where $\dot{S}_g$ is the entropy generation rate, $\dot{S}_f$ is the entropy flow rate into the system, $\Delta \dot{S}$ is the entropy change rate with time. However, $\Delta \dot{S}$ equals to zero when the system is steady state and thus $\dot{S}_g$ can be changed as

$$\dot{S}_g = -\dot{S}_f = \dot{S}_{f,out} - \dot{S}_{f,in} \quad (14)$$

where $\dot{S}_{f,out}$, $\dot{S}_{f,in}$ are the entropy flow out of and into the system.

$$\dot{S}_{f,in} = \int_{T_0}^{T_{h,in}} \frac{C_h dT}{T} + \int_{T_0}^{T_{c,in}} \frac{C_c dT}{T} = C_h \ln \frac{T_{h,in}}{T_0} + C_c \ln \frac{T_{c,in}}{T_0} \quad (15)$$

$$\dot{S}_{f,out} = \frac{\dot{Q}_0}{T_0} \quad (16)$$

In Eq. (16) $\dot{Q}_0$ is the heat flow released to the environment

$$\dot{Q}_0 = C_h(T_{h,in} - T_0) + C_c(T_{c,in} - T_0) - \dot{W} \quad (17)$$

C_h is the heat capacity flow rate of hot stream $C_h = c_h \dot{m}_h$, and C_c is that of the cold stream $C_c = c_c \dot{m}_c$.

Combining Eqs. (15)–(17) with Eq. (14) gives

$$\dot{S}_g = C_h \ln \frac{T_0}{T_{h,in}} + C_c \ln \frac{T_0}{T_{c,in}} + \frac{C_h(T_{h,in} - T_0) + C_c(T_{c,in} - T_0)}{T_0} - \frac{\dot{W}}{T_0} \quad (18)$$

The concept of entransy loss rate is defined by Cheng and Liang [43], which equals to the difference between entransy into and out of the system

$$\dot{G}_{loss} = \dot{G}_H - \dot{G}_L \quad (19)$$

where $\dot{G}_H$ is the entransy flows into the system, in ORC system,

$$\dot{G}_H = \frac{1}{2} C_h (T_{h,in}^2 - T_0^2) \quad (20)$$

$\dot{G}_L$ is the entransy flows out of the system which can be also extended in ORC system as

$$\dot{G}_L = \frac{1}{2} C_c (T_0^2 - T_{c,in}^2) + \dot{Q}_0 T_0 \quad (21)$$

where the first term on the right side is the net entransy flow rate taken in from the cold stream. The second term is the entransy loss rate due to the heat flow released into the environment.

Based on Eqs. (20) and (21), Eq. (19) can be changed into

$$\dot{G}_{loss} = \frac{1}{2} C_h (T_{h,in}^2 - T_0^2) + \frac{1}{2} C_c (T_{c,in}^2 - T_0^2) - \dot{Q}_0 T_0 \quad (22)$$

To combine it with Eq. (17), we can get

$$\dot{G}_{loss} = \frac{1}{2} C_h (T_{h,in} - T_0)^2 + \frac{1}{2} C_c (T_{c,in} - T_0)^2 + \dot{W} T_0 \quad (23)$$

The entransy dissipation is also discussed in this paper for the system optimization, which equals to the difference between the entransy loss and the entransy variation (work entransy) due to heat-work conversion [43]. The total entransy dissipation rate of the ORC system includes three parts,

$$\begin{aligned} \dot{G}_{dis} = & \left\{ \frac{1}{2} C_h (T_{h,in}^2 - T_{h,out}^2) - \left[\frac{1}{2} Q_{6,7} (T_6 + T_7) + Q_{7,8} T_8 + \frac{1}{2} Q_{1,8} (T_1 + T_8) \right] \right\} \\ & - \left\{ \frac{1}{2} C_c (T_{c,out}^2 - T_{c,in}^2) - \left[\frac{1}{2} Q_{4,5} (T_4 + T_5) + Q_{3,4} T_4 + \frac{1}{2} Q_{2,3} (T_2 + T_3) \right] \right\} \\ & + \left\{ \left[\frac{1}{2} C_h (T_{h,out}^2 - T_0^2) + \frac{1}{2} C_c (T_{c,out}^2 - T_0^2) \right] - [C_h (T_{h,out} - T_0) T_0 + C_c (T_{c,out} - T_0) T_0] \right\} \end{aligned} \quad (24)$$

the first one is the entransy dissipation rates due to heat transfer between the hot stream and the working fluid, which is braced as the first part on the right side in Eq. (24). As the same principle goes, the second brace is the entransy dissipation rates resulted from heat transfer between the working fluid and the cold stream. The last part in the third brace is the entransy dissipation rates caused by dumping the used streams into the environment.

The concept of entransy efficiency, defined by Guo and Huai [53] when they analyzed the chemical heat pump, is also investigated.

$$G^* = \frac{G_{f,out}}{G_{f,in}} = \frac{G_L}{G_H} \quad (25)$$

In addition, the revised entropy generation number [44,54] is also considered,

$$N_{RS} = T_0 \dot{S}_g / \dot{Q}_{out} \quad (26)$$

The concept of exergy destruction rate $\dot{E}_d$ is also utilized for the system optimization. Exergy is a substitute of available energy (effective energy) in thermodynamics. Analysis of exergy as an energy conversion coefficient considers not only the quantity, but also the quality of the energy, which can more profoundly reveal the essence of energy conversion and loss than energy analysis does.

The exergy destruction rate in the evaporator

$$\dot{E}_{d,evap} = \dot{m}_r (e_6 - e_1) + \dot{m}_h (e_9 - e_{12}) \quad (27)$$

The exergy destruction rate in the expander

Table 1

Basic thermodynamic and environmental properties of the working fluids.

Working fluid	t_{cr} (°C)	P_{cr} (MPa)	t_{fp} (°C)	t_{bp} (°C)	Safety	ODP	GWP	M
R123	183.7	3.668	−107.2	27.79	B1	0.012	120	152.9
N-pentane	196.5	3.364	−129.7	35.87	A3	0	11	72.15

Table 2

Assumptions for streams and components.

Parameter	Sign	Unit	Value
The environment temperature	T_0	K	288.15
Specific heat of the hot stream	c_h	kJ/(kg K)	1.025
The temperature of the cold stream	$t_{c,i}$	K	288.15
The flow rate of the cold stream	$\dot{m}_c$	kg/s	1.8
Specific heat of the cold stream	c_c	kJ/(kg K)	4.184
Degree of superheating	T_{sup}	K	5
Degree of subcooling	T_{sub}	K	3
Minimum heat transfer temperature difference in evaporator	ΔT_{evap}	K	5
Minimum heat transfer temperature difference in condenser	ΔT_{cond}	K	5

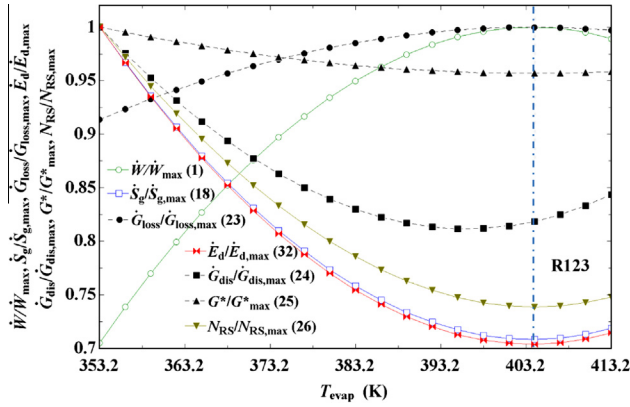


Fig. 3a. Variations of the evaluation parameters with evaporation temperature in the case of prescribed hot and cold streams for R123.

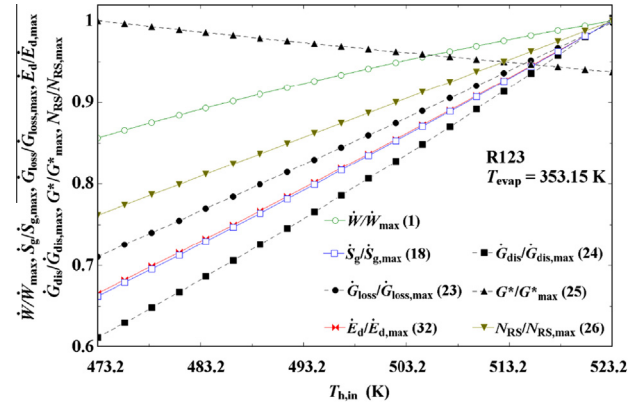


Fig. 4a. Variations of the evaluation parameters with hot stream inlet temperature at evaporation temperature = 353.15 K for R123.

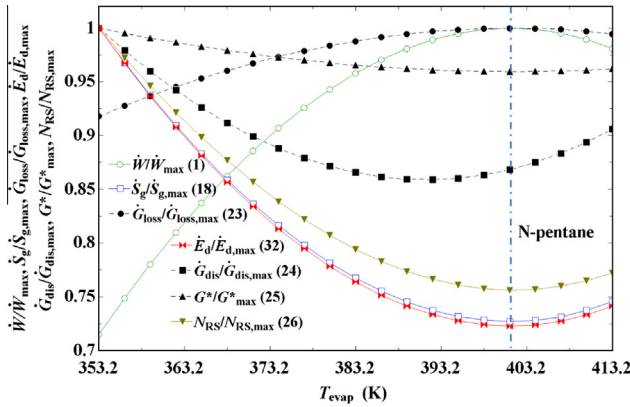


Fig. 3b. Variations of the evaluation parameters with evaporation temperature in the case of prescribed hot and cold streams for N-pentane.

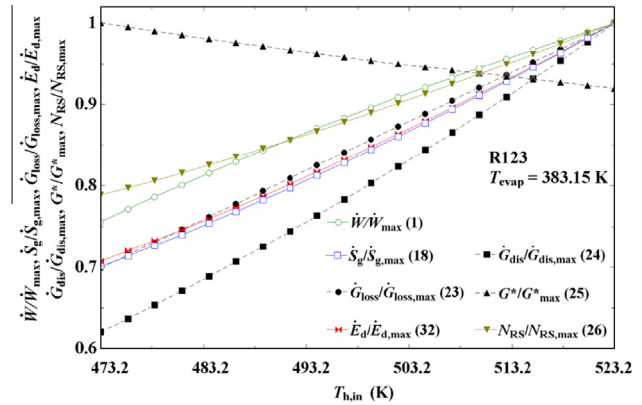


Fig. 4b. Variations of the evaluation parameters with hot stream inlet temperature at evaporation temperature = 383.15 K for R123.

Table 3
Representative thermodynamic and parametric data of R123 and N-pentane at optimized T_{evap} .

		R123		N-pentane	
		$T_{\text{evap}} = 403.85 \text{ K}$		$T_{\text{evap}} = 401.35 \text{ K}$	
$T_{h,\text{out}}$ (K)	$\dot{Q}$ (kW)	346.05	20.84	342.78	20.33
T_{cond} (K)	$\dot{S}_g$ (kW/K)	303.18	0.05173	303.17	0.05351
$T_{c,\text{out}}$ (K)	$\dot{G}_{\text{loss}}$ (kW K)	299.59	20,536	300.02	20,389
$\dot{W}_{1,2}$ (kW)	$\dot{E}_d$ (kW)	21.26	14.59	20.66	15.1
$\dot{W}_{5,6}$ (kW)	$\dot{G}_{\text{dis}}$ (kW K)	0.44	8083	0.33	8800
$\dot{Q}_{\text{evap}}$ (kW)	G^*	106.95	0.6566	109.7	0.659
$\dot{Q}_{\text{cond}}$ (kW)	N_{RS}	86.13	0.1102	89.37	0.1136

$$\dot{E}_{d,\text{exp}} = \dot{m}_r(e_1 - e_2) - \dot{W}_{1,2} \quad (28)$$

The exergy destruction rate in the condenser

$$\dot{E}_{d,\text{cond}} = \dot{m}_r(e_2 - e_5) + \dot{m}_c(e_{13} - e_{16}) \quad (29)$$

The exergy destruction rate in the working fluid pump

$$\dot{E}_{d,\text{pump}} = \dot{m}_r(e_5 - e_6) + \dot{W}_{5,6} \quad (30)$$

The exergy destruction rate due to dumping the used streams into the environment

$$\dot{E}_{d,\text{dump}} = \dot{m}_h e_{12} + \dot{m}_c e_{16} \quad (31)$$

Thus, the total exergy destruction rate of the ORC system

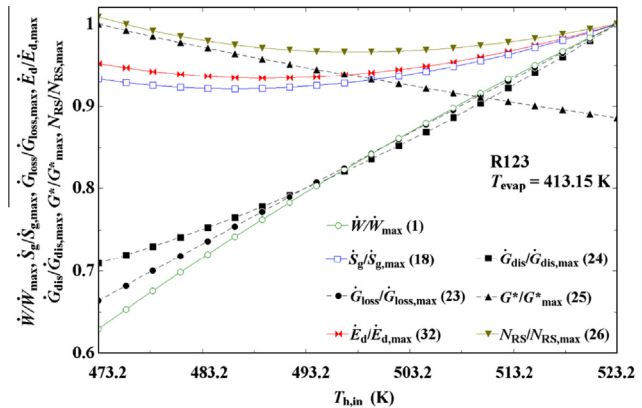


Fig. 4c. Variations of the evaluation parameters with hot stream inlet temperature at evaporation temperature = 413.15 K for R123.

$$\dot{E}_{d,\text{total}} = \dot{E}_{d,\text{evap}} + \dot{E}_{d,\text{exp}} + \dot{E}_{d,\text{cond}} + \dot{E}_{d,\text{pump}} + \dot{E}_{d,\text{dump}} \quad (32)$$

4. Global model

4.1. Working fluid

Working fluids have great influence on system safety, environmental protection and economic efficiency of ORC system. Numerous researchers have carried out extensive and in-depth working

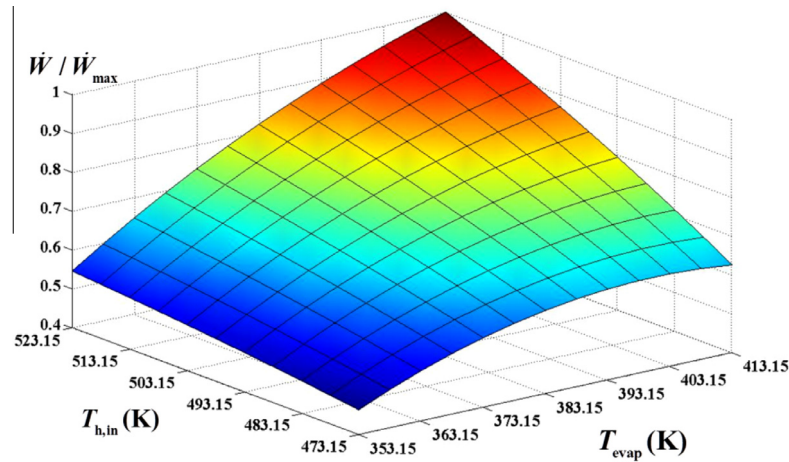


Fig. 5. Variations of the power output with both hot stream temperature and evaporation temperature for R123.

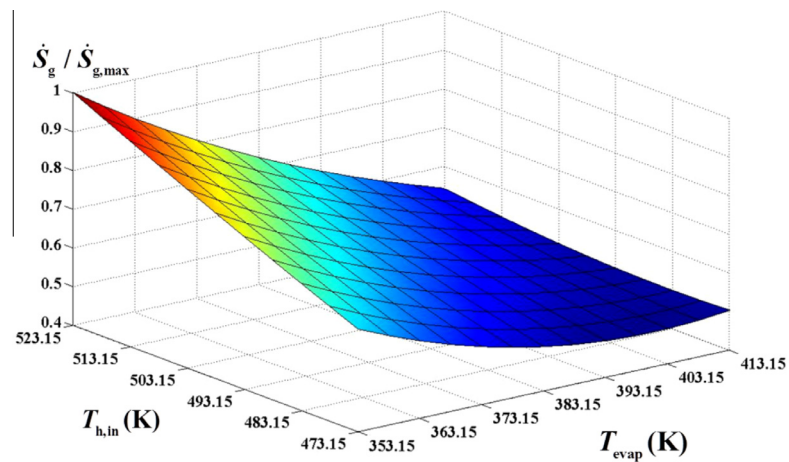


Fig. 6. Variations of the entropy generation rate with both hot stream temperature and evaporation temperature for R123.

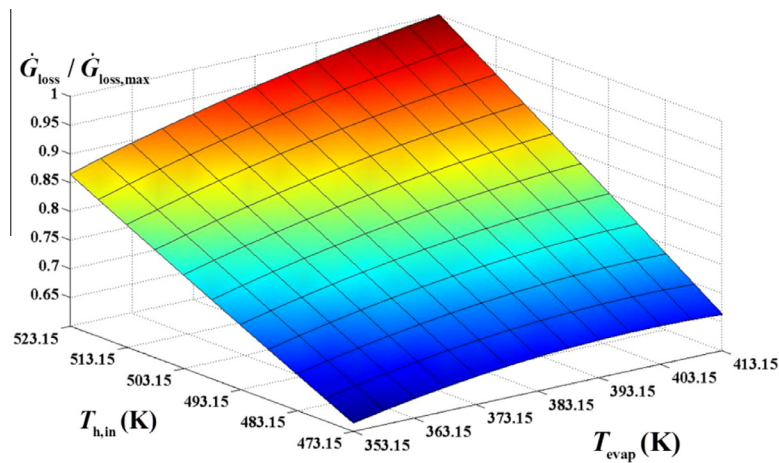


Fig. 7. Variations of the entransy loss rate with both hot stream temperature and evaporation temperature for R123.

medium selection researches [27–29,55–62]. Applicable fluids with good thermodynamics, chemistry, environmental protection, safety and economic characteristics, such as a fluid with low liquid specific heat, viscosity, toxicity, flammability, ozone depletion potential (ODP), global warming potential (GWP) value and price has more potential to be widely recommended and accepted.

Based on the previous criteria, two commonly utilized working fluids – R123 and N-pentane are chosen for comparison in this

paper. Basic thermodynamic and environmental properties of the fluids selected are shown in Table 1.

4.2. Assumptions

While giving the global model, in order to simplify the complexity and computing, we make some assumptions of unchanged

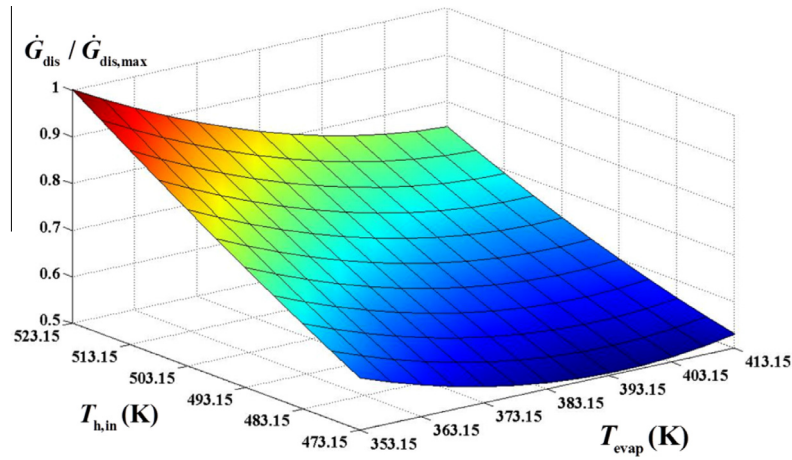


Fig. 8. Variations of the entransy dissipation rate with both hot stream temperature and evaporation temperature for R123.

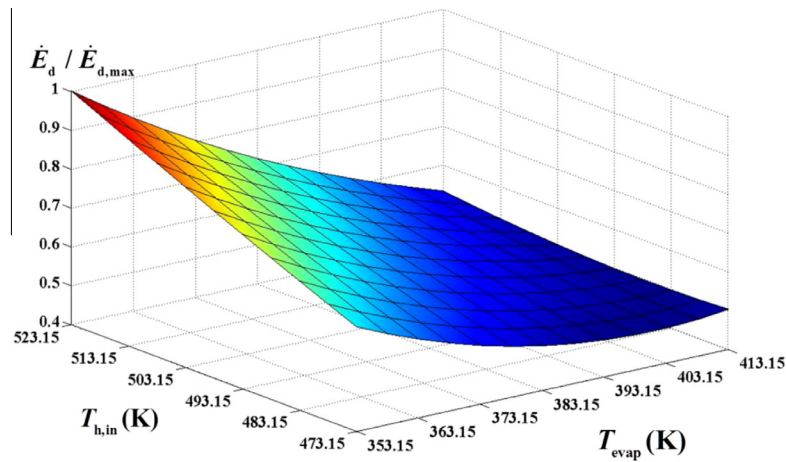


Fig. 9. Variations of the exergy destruction rate with both hot stream temperature and evaporation temperature for R123.

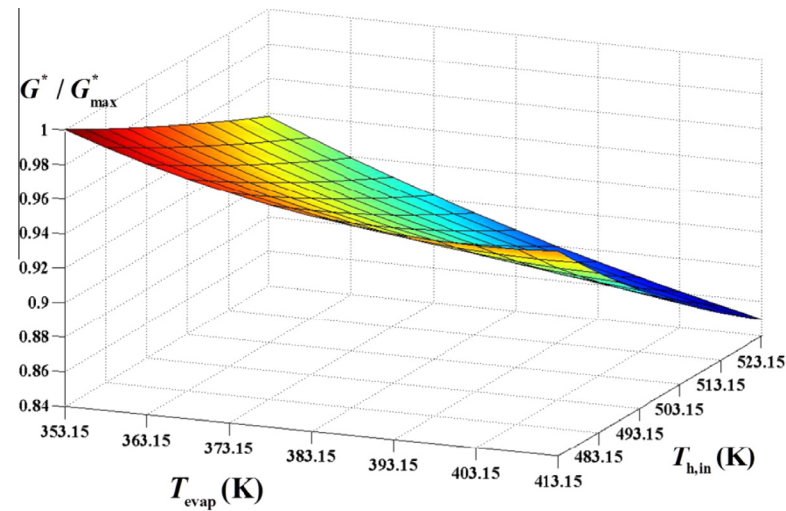


Fig. 10. Variations of the entransy efficiency with both hot stream temperature and evaporation temperature for R123.

parameters which are not the key points and will not significantly affect the accuracy of the calculation in Table 2.

Hot air whose humidity ratio is 4% is used to imitate the hot stream. Water of general environment condition is utilized as the cold stream.

5. Results and discussion

In this section, prescribed hot and stream conditions are considered as the first case for both R123 and N-pentane. Through the comparison, the law of the changes and trends for the optimization

for the ORC can be got. Next, variable hot stream condition are taken into account, since the results for the two working fluids are extremely similar under this condition, the research for R123 is only showed as a typical case of ORC.

5.1. Case I: Prescribed hot and cold stream conditions

This case input data are $T_{h,in} = 473.15$ K, $\dot{m}_h = 0.83$ kg/s, and $T_{c,in} = 288.15$ K, $\dot{m}_c = 1.8$ kg/s. T_{evap} varies from 353.15 K to 413.15 K. For the ORC the evaporation temperature is the only free parameter left in this case. This range of T_{evap} is chosen since it has already shown the change rules of the optimization criteria, meanwhile T_{evap} must be lower than the critical temperatures T_{cr} of both working fluids.

The calculated variations of the output power $\dot{W}$, entropy generation rate $\dot{S}_g$, entransy loss rate $\dot{G}_{loss}$, exergy destruction rate $\dot{E}_d$, entransy dissipation rate $\dot{G}_{dis}$, entransy efficiency G^* and revised entropy generation number N_{RS} with the evaporation temperature T_{evap} are shown in Fig. 3a for R123 and Fig. 3b for N-pentane.

Fig. 3a indicates that among the seven parameters, the minimum entropy generation rate, exergy destruction rate, entransy efficiency, revised entropy generation number and maximum entransy loss rate are corresponding to the maximum output power. However, the minimum entransy dissipation rate does not associate with the output power variation, it can be explained as follow: the entransy dissipation is one part of the entransy loss rate besides entransy variation (work entransy) or does not consider the influence of work output on the change of entransy.

The similar change laws are demonstrated in Fig. 3b for N-pentane under the same stream conditions. It is worth pointing out that compared to the optimized evaporation temperature for R123, the one for N-pentane appears earlier. 403.85 K and 401.35 K are the optimized temperature for R123 and N-pentane respectively. Other thermodynamic and parametric data at optimized T_{evap} for both working fluids of R123 and N-pentane are listed in Table 3.

Through Table 3, it can be obtained that R123 has a higher output power $\dot{W} = 20.84$ kW, which is 2.45% more than that of N-pentane. However, the $T_{h,out}$ of N-pentane is 3.27 K lower than the one of R123 means less energy released into the environment. In another word, R132 has better heat-power conversion capacity attributing to less energy was absorbed and more power was outputted in this case. In spite of more outstanding performances of R123, higher $T_{h,out}$ will lead to more serious thermal pollution.

For this case where the inlet temperatures, the mass flow rates and the heat capacities of the streams are fixed, all the entropy

principle, exergy theory, entransy loss rate and entransy efficiency are applicable to the optimization of the ORC, while the entransy dissipation is not. This conclusion is available no matter what working fluid is used, nevertheless, the system performances and parameters may be much different.

5.2. Case II: Variable hot stream temperature

In this case, variable hot stream temperature $T_{h,in}$ is taken into account. Since the results for the two working fluids are extremely similar, we only illustrate the research for R123 as a typical case of ORC. It is set that $\dot{m}_h = 0.83$ kg/s, and $T_{c,in} = 288.15$ K, $\dot{m}_c = 1.8$ kg/s. T_{evap} varies from 353.2 K to 413.15 K, and $T_{h,in}$ varies from 473.15 K to 523.15 K. In order to observe the distinctions at different T_{evap} , the curves at 353.15 K, 383.15 K and 413.15 K are captured equidifferently as Figs. 4a–4c. In Fig. 4a, all the parameters increase with the increasing $T_{h,in}$ besides the entransy efficiency G^* at $T_{evap} = 353.15$ K. This law is continued at $T_{evap} = 383.15$ K as shown in Fig. 4b only in addition to some different changing proportions. However, changes occur in Fig. 4c, there are inflection point on the curves of the entropy generation rate $\dot{S}_g$, the exergy destruction rate $\dot{E}_d$ and the revised entropy generation number N_{RS} . As a result, it is summarized that in this case, the entransy loss rate $\dot{G}_{loss}$ and entransy dissipation rate $\dot{G}_{dis}$ always have the same increasing tendency with the output power rate $\dot{W}$, while the entransy efficiency G^* has the opposite one.

For further discussion, more detailed 3-D coordinates (Figs. 5–11) are utilized to observe the global variation of parameters with T_{evap} and $T_{h,in}$. It is depicted in the 3-D picture that the surface of the entransy loss rate $\dot{G}_{loss}$ in Fig. 7 is similar to that of the power output $\dot{W}$ in Fig. 5, but the entransy efficiency G^* always has the opposite variation. If $T_{h,in}$ is constant, entropy generation rate $\dot{S}_g$, the exergy destruction rate $\dot{E}_d$ and the revised entropy generation number N_{RS} will be suitable to the optimized power output as discussed in Case I, however, when it is extended to the 3-D, the result will not the same. Although the entransy dissipation rate $\dot{G}_{dis}$ (Fig. 8) in Case II has the same variation tendency with the power output $\dot{W}$, its utilization has already been excluded in Case I.

5.3. Case III: Variable hot stream mass flow rate

In this case, a variable hot stream mass flow rate $\dot{m}$ condition is considered. The same as above, the research for R123 is only illustrated since the results for N-pentane are alike. Input data are $T_{h,in} = 473.15$ K, and $T_{c,in} = 288.15$ K, $\dot{m}_c = 1.8$ kg/s. $\dot{m}_h$ varies from 0.7 to 1 kg/s. Three T_{evap} at 353.15 K, 383.15 K and 413.15 K are

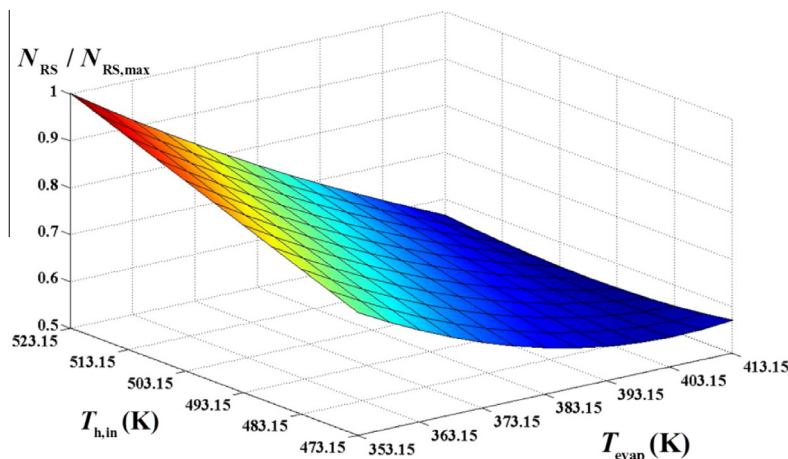


Fig. 11. Variations of the revised entropy generation number with both hot stream temperature and evaporation temperature for R123.

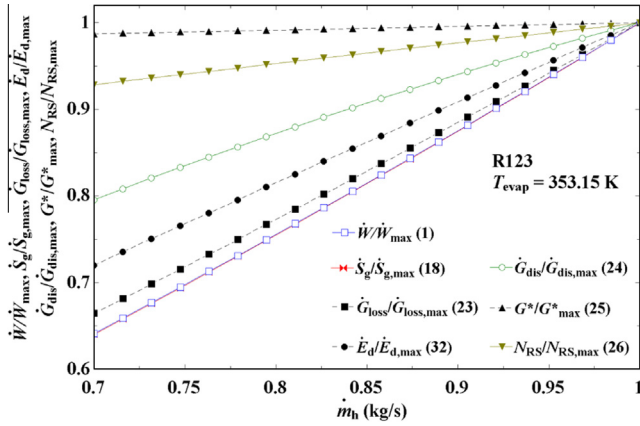


Fig. 12a. Variations of the evaluation parameters with hot stream flow rate at evaporation temperature = 353.15 K for R123.

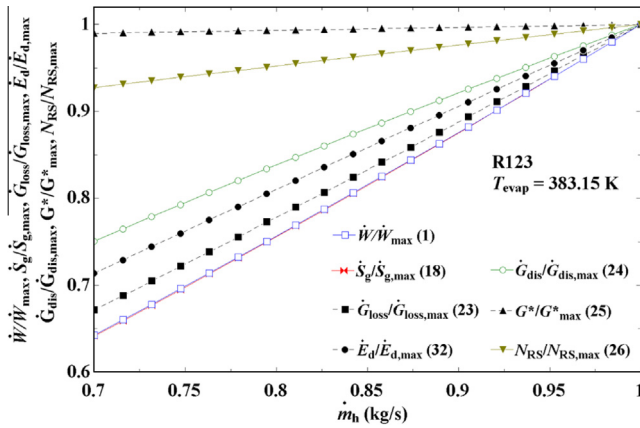


Fig. 12b. Variations of the evaluation parameters with hot stream flow rate at evaporation temperature = 383.15 K for R123.

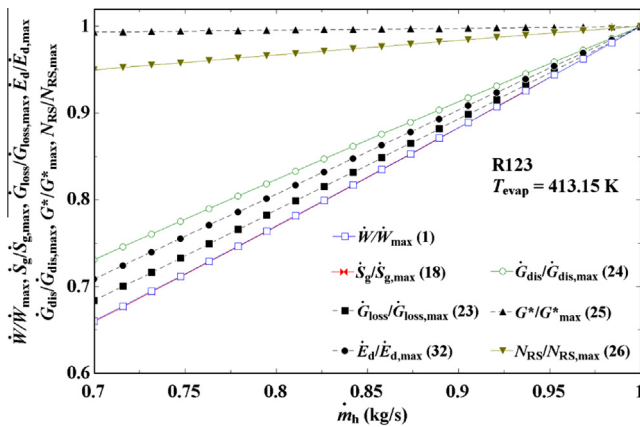


Fig. 12c. Variations of the evaluation parameters with hot stream flow rate at evaporation temperature = 413.15 K for R123.

given for contrast. All the parameters increase with the hot stream flow rate $\dot{m}_h$ rise in this case. Since the curve laws can be easily observed in Fig. 12, 3-D meshes are no more plotted for discussion.

After the integration of the three cases above, the entransy loss rate $\dot{G}_{loss}$ is confirmed to be the only parameter suitable for all three cases.

6. Conclusions

In the present study, analyses of entropy, entransy and exergy are applied to the optimization of the Organic Rankine Cycle operating on R123 and N-pentane. Three different common cases which are variable evaporation temperature, hot stream temperature and hot stream mass flow rate have been taken into account to explore the applicability of the parameters. The investigations are carried out through a computer programming in Engineering Equation Solver Ver. 8 which includes the working fluids' properties. The main conclusions can be summarized as follows:

- (1) The theory of entransy is proposed for Organic Rankine Cycle optimization including entransy loss, entransy dissipation and entransy efficiency, as well as the concepts of entropy generation and exergy destruction. The applicabilities of the entropy generation rate $\dot{S}_g$, entransy loss rate $\dot{G}_{loss}$, entransy dissipation rate $\dot{G}_{dis}$, entransy efficiency G^* , revised entropy generation number N_{RS} and exergy destruction rate $\dot{E}_d$ to optimization of the ORC are discussed in three cases.
- (2) R123 and N-pentane are selected as the working fluids, detail comparisons are proceeded under constant $T_{h,in}$ condition. Although the optimal evaporation temperature and optimized output power is different, but the change laws of the parameters are same. Thus the applicability bellow can be verified no matter whatever the working fluid is used.
- (3) After comparing prescribed and variable hot stream cases, it can be summarized that larger entransy loss rate invariably corresponds to larger power output. The concept of entransy loss is appropriate for the optimization of the ORC for all the cases discussed in this paper. The concept of entropy and exergy can be only utilized under fixed stream conditions.

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